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The overall objective of this work is to introduce a drastically innovative technology for repair and automatic extraction of high-order geometric data from platform models developed with CAD (Computer Aided Design) software tools. The results will have appliations to large-scale CEM analysis of low observable aircraft by high-order fast solvers as well as to a variety of other computational problems requiring high accuracy geometry representation. The effort carried out under this project was planned as an assessment of the current capabilities of GeomFix, a software system developed recently by Matis for efficient and reliable repair of geometric deficiencies in CAD models intended for use with computational electromagnetics methods.

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New Methods for Repair of Geometry and Topology of CAD Models

Final Technical Report

The Work Described in This Report Was Performed by Matis, Inc.

Under Sponsorship by

DARPA - Defense Sciences Office

Contract F49620-01-C-0050 to AFOSR

December 2002

Preface

The work presented in this report was performed by Matis, Inc. at 1255 Biltmore Drive, Atlanta, Georgia 30329 in cooperation with Lockheed Martin Missiles and Fire Control-Orlando at 5600 Sand Lake Road, MP 224, Orlando, Florida 32819-8907.

This work was sponsored by DARPA - Defense Sciences Office through a contract with the Air Force Office of Scientific Research. The work was performed during the period September 15, 2001 - December 15, 2002. The project Technical Monitors were Drs. Dennis Healey, Douglas Cochran and Carey Schwartz from DARPA and Dr. Arje Nachman from AFOSR.

Organization of the Report

This report consists of two parts. The present part describes the overall structure of the effort, its results, and conclusions. It also describes specific contributions by the Matis team not reflected or only partially reflected in part II. The part II is an appendix submitted as a separate volume. It contains the final report prepared independently by the Lockheed Martin team.

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1 Executive Summary

The overall objective of this work is to introduce a drastically innovative technology for repair and automatic extraction of high-order geometric data from platform models developed with CAD (Computer Aided Design) software tools. The results will have applications to large-scale CEM analysis of low observable aircraft by high-order fast solvers as well as to a variety of other computational problems requiring high-accuracy geometry representation.

The effort carried out under this project was planned as an assessment of the current capabilities of GeomFix, a software system developed recently by Matis for efficient and reliable repair of geometric deficiencies in CAD models intended for use with computational electromagnetics methods.

The work was performed in close collaboration between Matis, Inc. and three divisions of Lockheed Martin Corporation: Lockheed Martin Missiles and Fire Control (LMMFC) in Orlando, Florida, Lockheed Martin Aeronautics Company (LM Aero) in Palmdale, California, and Ft. Worth, Texas, and Lockheed Martin Naval Electronics and Surveillance Systems - Surface Systems (LM NE&SS-SS), Moorestown, New Jersey.

The assessment was performed by:

1. Interactive demonstrations of GeomFix in various divisions of Lockheed Martin and at Matis' office in Atlanta. 43 people participated in these demonstrations.

2. Training in GeomFix provided by Matis to four groups of engineers from Lockheed Martin, AFRL, and DARPA.

3. Repair by Matis personnel of CAD models selected by Lockheed Martin and approved by AFRL and DARPA. The validation of repaired models was based on independent verification that repaired models are free of geometric defects and on comparison of RCS's obtained on original and repaired models.

4. Use of GeomFix by personnel from Lockheed Martin to independently replicate the repair process on models repaired by Matis.

5. Use of GeomFix by Lockheed Martin teams for repairing CAD models of aircraft and naval surface ships not available to Matis.

In addition, algorithms and codes facilitating this assessment and in many cases significantly enhancing the capabilities of GeomFix were developed and implemented by Matis during this phase.

Based on the assessment, recommendations for additional developments of this technology have been proposed. Recommendations for enhancements and additions to GeomFix impacting its immediate use and distribution have also been proposed.

The overall result of this assessment is an extremely enthusiastic endorsement of the quality and potential of the new technology provided by GeomFix.

The final conclusion of the assessment as stated by Lockheed Martin is as follows (see page 3 of Final Report by Lockheed Martin attached to this report):

"GeomFix is a very robust, versatile and reliable software environment for preprocessing CAD models for CEM analysis. It is a tool critically needed for CEM analysis of LO platforms. Its rigorous mathematical foundation provides confidence in its reliability. GeomFix currently has many desirable CAD repair features that the three divisions of Lockheed Martin have been trying to develop on their own. The open architecture of GeomFix provides a robust framework for enhancements, With the inclusion of the recommendations in the next phase, we believe that GeomFix will be universally applicable to the Lockheed Martin CEM efforts for DOD programs and platforms."

2 The GeomFix System - Overview

2.1 Background

With rapid development and extensive spread of CAD/CAM and scanning technologies, the notion of re-using available CAD models for engineering analysis has become very attractive. In computational electromagnetics (CEM) this trend has been strongly motivated by recent advances in computational techniques capable of performing electromagnetic (EM) analysis on complete structures, such as an entire aircraft. The high efficiency of new algorithms along with continuous improvements in computer technology deliver promising opportunities for fast and accurate practical applications.

Any code performing electromagnetic calculations on a geometrically complex structure requires, as a part of the input, an accurate representation of this structure in the form of a high fidelity electronic model. However, in order for the model to be acceptable to a particular computational software, it must satisfy a set of specific requirements determined by the design and algorithms of this software.

Almost all physical structures, such as aircraft, ships, missiles, etc., started life as CAD models. However, CAD models developed for a particular purpose (for example, for manufacturing) may be completely useless for purposes other than those of the original designer. In addition, CAD software systems produce a representation of the model in some electronic format, usually specific to the utilized CAD system. In order to facilitate data exchange, various translators/converters have been developed. For example, some electromagnetic applications require translation of surfaces generated as connected patches of NURBS (Non-Uniform Rational B-Splines) into the unstructured grids across these connected patches. Such translation/conversion can be a very complex process, and certain information may be lost or distorted in this process. This, too, leads to irregularities and defects in most of the available CAD models. As a result, extraction of computational meshes of required quality from these models is a task of large complexity with many unsolved problems.

Among the typical irregularities observed in CAD models which preclude their use for CEM are overlapping parts, branching facets, disconnected surfaces, missing facets, adjacent facets with sides that do not match, degenerate facets, inconsistent facet orientation, bad aspect ratios, unavailability or incorrect assignment of material properties information, inadequate description of actual singularities, such as corners, gaps or edges, and excessively refined representation of smooth surfaces. CAD models represented by splines in IGES (Initial Graphics Exchange Specification) or other formats suffer from similar problems. The observed irregularities can be traced to several different sources: legacy models, sloppy design practices, translation/conversion between different CAD modeling systems, high demand for re-use of existing CAD models for tasks not foreseen by the original designer, specific requirements imposed by computational codes in downstream applications, etc.

Some of the quite typical representative deficiencies found in the original models supplied by Lockheed Martin for this effort are given on page 6.

Summary of Deficiencies Exhibited by 4 Models Provided Prior to Down Select

Summary of Repair Jobs Based on CEM Code Requirements				
Intended CEM Code	X-Patch		MM3D	
Model	Case 1	Case 2	Case 3	Case 4
Description	Missile	Heli-copter	Generic Fighter	VFY218
1. Degenerate facet (those with only 2 distinct vertices/nodes).	X			
2. Facet internal angles < 10 degrees (MM3D requirement).			X	X
3. Facet internal angles < 5 degrees (Xpatch requirement)	X	X	X	
4. Bad aspect ratios.	X	X	X	X
5. Ratio of longest edge in mesh to shortest edge in mesh > 100.			X	X
6. Intersecting-penetrating facets	X	X	X	
7. Gaps between platform parts	X		X	X
8. Overlapping facets	X	X	X	X
9. Topologically disjoint components	X	X	X	X
10. Missing surface parts			X	X
11. T- Junctions			X	X
12. Edges shared by 3 or more facets not in the same plane.			X	
13. Irrelevant internal parts			X	X
14. Inconsistent orientation			X	

In the aircraft industry, building a high fidelity aircraft model suitable for electromagnetic calculations is an expensive and time-consuming task. Consequently, it is highly desirable to develop capabilities to transform existing CAD models into models suitable for variety of EM computations. Of course, it should be realized that realistic surface modeling will be useful in solving computational problems only if appropriate algorithms, capable of performing required computations on realistic models (or meshes derived from them), are available. Computational algorithms often depend, in a significant way, on the specific geometric assumptions used in building the model and will not work or will produce erroneous results if these assumptions are not satisfied.

2.2 GeomFix - an Interactive System for Diagnostics and Repair of CAD models

The overall focus of this effort is development of an innovative method complete with mathematical descriptions of surface properties and possible surface defects, robust computational algorithms and software codes, and computer graphics integrated into an environment for CAD model transformation. Such a method, when implemented, will enable utilization of vast number of existing CAD models for tasks arising in computational electromagnetics. Given the requirements of an existing or future computational application, technicians with some prior training will be able to perform a quick and reliable conversion of virtually any CAD-generated representation of a geometrically and topologically complex structure into a model suitable for deriving meshes that satisfy these requirements.

In order to deal with the tremendous complexity of the task of CAD model repair, we choose not to put an emphasis on any one-size-fits-all method. Our approach is pragmatic and combines formerly mutually exclusive methods, such as

- totally automatic vs. with user intervention,
- global vs. local
- reuse existing vs. build new

We do not suggest an all encompassing fully automated push-a-button transformation, which may produce disastrous results. Instead we will offer a great variety of fast and sound automated tools that can be interactively tuned by the operator, thus benefiting from human interface when needed. In particular, the selective repair method allows one to mark actual singularities in order to assure that they remain intact. Certain operations, such as mesh refinement, may be sorely needed on one part of the surface, and yet would introduce a substantial decrease in the speed of computations elsewhere. Applying the refinement algorithm locally will solve this dilemma. Correcting the inconsistency of the orientation, on the other hand, is often desired as a global operation. Our answer to "reuse-existing or build-new" question is "BOTH". Existing CAD models are used and combined with other surfaces, either from the data bases or generated by the user, when there is a need for a partial replacement.

Our approach is to provide an interactive environment with interconnected components. The process of model correction begins with loading an electronic file representing the

original model. The actual properties of the loaded model are immediately visualized and a hierarchy tree associated with a multi-part model is automatically built. Internally, the geometric properties of the loaded surface are represented as mathematical equations.

Automatic diagnostic procedures identify defects of the model. A data base containing mathematical descriptions of possible defects is used in this step. Results of diagnostics are presented to the user both as data and visually, along with the recommended framework for handling each identified defect. The framework is a short sequence of steps to follow, each step being an application of a construction, repair, or diagnostics tool which, when performed, invokes appropriate visualization tools, data bases and links. Thus an overall process of model repair can be thought of as a sequence of templates. The frameworks do not limit flexibility, but reduce unnecessary work. Such an approach provides an engineer with a plan of action, yet offers the flexibility to modify the plan as the treatment progresses.

The visualization tools support both surface display and surface manipulation functions. As the user requests certain modifications of geometric properties of the surface, the system will determine whether such modifications are possible and respond with notification if they are not. This early warning will preclude construction of ambiguous, incompatible, inconsistent, or impossible objects, thus drastically reducing the efforts and increasing productivity. All requested modifications that are determined by the system to be valid will be automatically generated.

In order to reduce significantly the time, cost, and effort required for preparing the geometry and topology of CAD models for use by CEM codes, our proposed interactive approach brings together a powerful combination of efficient algorithms, computer graphics, database management, a balance between totally automated solutions and solutions based on human intervention, preventive early warning systems, and well thought through guidance.

Since 1995, the Matis' research team has been working on problems of platform modeling for CEM. We have developed a number of fast and robust computational engines for use in re-engineering existing electronic models and accommodating them to engineering analysis. The proposed method has been prototyped and tested for faceted models, and showed very favorable results in terms of ease of use, high productivity, and superior quality of the obtained platform geometry representation. The faceted models repaired with the developed tools have been successfully used in DoD applications of solving CEM tasks using fully operational codes with stringent geometric requirements.

The proposed approach to model repair is not dependent upon any particular format for representing geometry. Our objective is to extend it to curved patches and provide the solution to the problem of geometry repair for high-order CEM methods. As a result of this effort and based on our experience, plans and ideas, the existing algorithms and codes will be expanded, enhanced, augmented and integrated into a preprocessing environment for bridging the gap between the legacy of CAD models and their use for CEM analysis.

2.3 Manifolds with Singular Metrics - A Mathematical Framework for Analysis and Transformation of CAD Models and Meshes

A fundamental problem associated with extraction of meshes from surfaces represented by CAD-generated models is connected with the fact that the errors produced in the process of replacing a smooth surface by a discrete mesh may be small only in some C^0 norm which depends on the geometry of the surface itself. Therefore, such a norm does not provide a realistic quantitative measure of "closeness" of the mesh to the surface. Obviously, for high-order methods with controllable accuracy, as required by the VET program, this issue is critical.

The same observation applies also to the problem of repairing CAD models. In this problem, one needs to restore (or rebuild) a part or parts of the model. Such restoration must be based on the available surface data, and an understanding and interpretation of the surface geometry is a necessary part of the repair process.

Fortunately, a rigorous mathematical framework for performing this kind of analysis of CAD generated surfaces is provided by the theory of Alexandrov spaces, which describes shapes using manifolds with singular metrics and for which analogues of many classical geometric quantities can be defined and investigated.

Alexandrov spaces are very general and include all two dimensional manifolds whose metrics can be locally uniformly approximated by Riemannian metrics with uniformly bounded integrals of the absolute value of the Gauss curvature. In particular, these spaces include surfaces represented by patches, that can be flat, created with NURBS, or a combination of both. They also include smooth surfaces. One of the fundamental properties of Alexandrov spaces is that the spaces themselves and the geometric quantities defined on them can be approximated by polyhedral surfaces and by appropriately defined on these polyhedral surfaces geometric quantities that can be efficiently computed.

The specific surface representation plays no role in these constructions, and this is a critical advantage of the proposed approach. In fact, using this property, it is possible to re-build the original subdivision of the model into patches to make it more suitable for smoothing and meshing.

The theory of Alexandrov spaces also contains also important approximation results (in appropriate norms) providing a natural way of estimating the curvatures on the limiting surfaces from geometric information computable on polyhedral surfaces. It should be noted that the above mentioned convergence results must be supplemented by a rigorous error analysis, which is currently not available. We intend to work on these and related problems and will apply this mathematical framework to geometric issues connected with the use of CAD models by fast CEM solvers.

3 Results

The description of the efforts carried out by the Lockheed Martin divisions is given in detail in the attached appendix prepared by the Lockheed Martin team and submitted as a separate volume. Here we describe the overall organization of the project. the contribution by the Matis' team, and a summary of results from the Final Report by Lockheed Martin.

3.1 Objectives of the Project

The main objective of the project was to perform an assessment of the GeomFix environment as a working prototype of a system with modular infrastructure capable of dramatic reduction in cost and human intervention time required to transform a given CAD (Computer Aided Design) model of a platform into a geometric representation suitable for use by a range of CEM analysis codes.

The assessment was performed by interactive demonstrations, training, repair process performed by Matis and its independent replication by the Lockheed Martin team. and documentation of the use of GeomFix when applied to a variety of faceted CAD models identified by Lockheed Martin and Matis and approved by DARPA and AFRL. In addition, algorithms and code developments required to complete this assessment were performed by Matis during this phase.

3.2 Team Members

- Matis, Inc. - prime contractor on the project
- Lockheed Martin Missiles and Fire Control (LMMFC), Orlando, Florida - subcontractor
- Lockheed Martin Aeronautics (LM Aero), Palmdale, California, and Ft. Worth. Texas - subcontractor
- Lockheed Martin Naval Electronics and Surveillance Systems - Surface Systems (LM NE&SS-SS), Moorestown, New Jersey - subcontractor

3.3 Tasks Performed

A detailed task schedule is presented in the chart on page 11. Here we provide brief descriptions of principal tasks performed under this effort.

Task Schedule: New Methods for Repair of Geometry and Topology of CAD Models

Tasks	Sub-Tasks	Description	Responsible Team	1	2	3	4	5	6	7	8	9	10	11	12
		Contract Award to Matis													
		Subcontract Award to LM													
1		**Define Requirements to Geometry and Topology**													
	1.1	Survey areas within LM where CAD models are used for CEM	LM												
	1.2	Review requirements to models for CEM codes currently in use or planned	Both												
2		**Training**													
	2.1	Provide qualified personnel to receive training from Matis for 1 week	LM												
	2.1A	Prepare training materials	MA												
	2.1B	Provide qualified personnel to conduct training	MA												
	2.2	Provide LM Systems Support for installation of GeomFix	LM												
	2.2A	Provide 4 annual licenses, install GeomFix at LM and Support	MA												
3		**Identify models and Develop validation Metrics**													
	3.1	Identify suitable models	Both												
	3.2	Evaluate the state of the models and determine/document needed repairs	Both												
	3.3	Establish validation metrics	Both												
	3.4	Assess current capabilities of GeomFix as applied to the identified tasks	Both												
4		**Add capabilities, perform repairs and evaluation**													
	4.1	Develop repair processes	MA w/LM												
	4.1A	Develop and implement additional capabilities identified in Subtask 3.4	MA												
	4.1B	Perform first cycle of model repairs	MA												
	4.2	Analyze repaired models and propose additional repair tasks	Both												
	4.2A	Develop and implement additional capabilities proposed in Subtask 4.2	MA												
	4.2B	Perform additional repairs	MA												
	4.3	Review models after additional repairs have been performed	Both												
	4.4	Replicate repair processes	LM												
	4.4A	Support replication of repair processes by LM	MA												
	4.4B	Prioritize / Integrate new developments into new release of GeomFix	MA												
5		**Final Assessment / Recommendations / Priorities**													
	5.1	Complete Assessment and Develop/document recommendations	Both												
	5.2	Establish priorities for upgrades/modifications/porting/integration	Both												
6		**Prepare Technical Documentation, Publications, Reports**													
	6	Prepare Technical Documentation, Publications, Reports	LM												
	6A	Prepare and integrate Technical Documentation, Publications, Reports	MA												
7		**Support/Attend/Present at EMCC, AFOSR/AFWL, DARPA Meetings/ws**	Both												

1. Reviewed requirements of CEM codes currently used at various divisions of Lockheed Martin and at Matis. In particular, the following codes were considered:

    - MM3D
    - X-Patch
    - Fisk
    - DOVA
    - C-DOVA
    - AAPG2000

2. Matis provided training in use of GeomFix to personnel from three divisions of Lockheed Martin and from AFRL.

3. Lockheed Martin provided Matis with four realistic CAD models: one of a missile and three of aircraft.

4. Matis identified geometric deficiencies in these models (see chart on page 6). Two models which contained all of the identified deficiencies were selected for repair and further analysis.

5. Matis' team repaired the models to required specifications.

6. Lockheed Martin teams evaluated the repaired models and determined that the repaired models satisfied the stated requirements.

7. Lockheed Martin teams ran CEM codes on the original and repaired models; in some cases up to 100% discrepancies in average RCS computed on the original and repaired models were found. Subsequent analysis showed that these discrepancies were caused by significant defects in the geometry of the original models.

8. Lockheed Martin teams used GeomFix to successfully perform an independent replication of required repairs. The RCS obtained with models repaired independently by Matis and Lockheed Martin were within $0.6dB$.

9. Lockheed Martin teams used GeomFix to successfully repair models not available to Matis, including surface ship models.

10. Matis upgraded GeomFix by adding a number of new capabilities, including many requested by the Lockheed Martin teams. In particular,

    - Building on and extending the work of Rivara, Matis developed and implemented a recursive Mesh Refinement (MR) algorithm capable of producing a refined mesh with resolution specified by the user in terms of edge length. The refined mesh has a provable lower bound on the smaller angle $\geq 1/2$ of the smallest angle in the original mesh. Thus, the quality of the mesh does not deteriorate in the process of refinement.This is an <u>extremely important</u> property of this algorithm.

- Application of the MR algorithm allows to produce meshes with the maximal edge length consistent with required frequency calculations.
- Matis developed and implemented a revolutionary algorithm for improving mesh quality (MQ) without compromising the original geometry. Meshes that contain elements with small angles are a well known "curse" of numerical calculations, typically leading to major numerical instabilities. The MQ algorithm developed by Matis solves this critical problem for faceted models.
- Numerous other new and/or enhanced features were added to GeomFix. These include: slicing and stitching, deleting T-junctions along a user selected curve, purging vertices with tolerance along a user selected curve, import/export capabilities in DXF format, expanded mesh quality and geometry information reports.

11. Recommendations were developed for next phase expansions, additional capabilities, porting, integration with ACAD and CEM codes, as well as technology insertion strategies.

4 Recommendations for Future Developments

4.1 Recommendations by Lockheed Martin

The recommendations for future additions and enhancements of GeomFix provided by Lockheed Martin are listed in the tables on pages 15 - 17. The top 5 upgrades recommended by each of the divisions of Lockheed Martin are listed in the table on page 18.

Due to several duplications in the Lockheed Martin lists of recommendations they were consolidated and categorized by Matis into 11 tasks presented in the table on page 19. The first 10 tasks on page 19 are prioritized in accordance with the order implied by Lockheed Martin's recommendations. The subtasks listed under task 11 have already been implemented by Matis in the most recent version of GeomFix.

4.2 Recommendations by Matis

- Continue implementing users' recommendations
- Using the environment of GeomFix, implement capabilities to support use of CAD models by high-order fast CEM solvers (this includes models represented by NURBS). This is a major task described in detail in the original proposal by Matis for the VET program.
- Continue adding tools and processes
- Expand import/export capabilities

Prioritized Recommendations from LMMFC-O

Relative Priority	DESCRIPTION
1	Provide Ability to places elements in different "groups", identified by different colors. This would allow assigning material properties to different elements in our CEM/RCS codes.
2	Provide Ability to detect partially overlapping facets.
3	Provide Ability to refine mesh using user-specified parameters such as maximum facet size, minimum angle, and minimum aspect ratio.
4	Provide Ability to rotate all or part of the geometry about a given line
5	Port GeomFix to Linux Operating System
6	Modify Decimation Triangulation Command to allow the user to define the maximum "error". The "error" is the degree to which the surface geometry is modified by the change in the angles between adjacent elements that occurs with the decimation command.
7	Modify the "distance" command to immediately display the distance between nodes without having to click again.
8	Modify Ability to export screenshots as a graphics file (.jpg or .gif)
9	Provide Ability to seed a mesh
10	Provide Ability to execute part or all of GeomFix using macros for multiple repetitive operations.
11	Provide Option for the user to set the default size of the node selection "diamonds", relative to the screen size. as the user zooms in or out
12	Complete the Investigation of the Integration of GeomFix with ACAD

Prioritized Recommendations from LM Aero (Palmdale and Fort Worth)

Relative Priority	DESCRIPTION
1	Provide Capability to support the identification, modeling, definition and repair of multiple dielectric materials and PEC regions including internal material boundaries that MM3D expects. Include a method to handle, store and define material values or tags as well as keeping this information in the output files
2	Provide Capability for the migration of element normal information across part boundaries defined by triplets (triangle edges shared by 3 or more triangles). MoM codes require material boundaries that result in triplets. Normal alignment is currently done at the Whole Model level.
3	Provide the capability to maintain the initial model geometry, level of curvature and part boundaries. Any action that will change the curvature of a part or change a boundary must have user concurrence.
4	Provide location and highlighting of facets with small angles in Mesh quality report. These small angle facets are often difficult and time consuming to locate with available techniques.
5	Provide an UNDO command. Commands can sometimes result in unwanted changes to the geometry. With the UNDO command, the user could simply back up one step, when something occurs that was unexpected.
6	Modify Delete T-Junction Command to add a proximity check when the vertices are very close together. If two vertices are within the proximity check value, merge the vertices instead of generating new facets that may overlap.
7	Provide an initial display of changes to user for acceptance prior to implementing to allow users to modify inputs to a function if they are inappropriate.
8	Modify the Stitch Part Together command to eliminate the extra part. Currently the command combines two parts into one, storing the final part into one of the original parts. However, the Replace operation only affects the final part name. This means that the added part still exists independently in the model.
9	Modify the user control of the Reduce Edge Length to allow cutting of individual facets or selected groups of facets in an orderly fashion. Provide a capability to specify where new vertices should be generated.
10	Add the capability to satisfy all mesh requirements, reduce GeomFix crashes and refine the GeomFix interface to improve usability features.
11	Provide capability to identify, flag and properly handle desirable "triplets." They are an integral geometry component of any model where more than two dielectric and/or PEC regions adjoin each other.
12	Provide a 'shrink' display mode
13	Provide capability to better handle curvatures, specifically where coarse facet align with fine facets. In this case the Delete T-Junction capability becomes error-prone due to the large gaps between the two sets of facets.
14	Provide capability for user to create vertices in several manners. I.e.: by x, y, z coordinates; by selecting two vertices and specifying the number of vertices to add between them; and by generating a curve and specifying the number of vertices to generate along the curve.
15	Modify Screen Pick Facets to allow greater capability for the user
16	Provide capability to create a display that shows solid with wire frame overlaid, a combination of the "As Is" and "Hidden Line" display options.
17	Complete investigation of techniques to assure conformity with the original geometry and implement the preferred approach
18	Modify Delete T-Junction Command to provide to specify minimum internal angle.
19	Modify Delete T-Junction Command to provide capability to cut multiple facets per command.
20	Provide geometry information without having to reuse the Replace command.
21	Allow user to flip the normal of individual facets or a set of facets selected via screen picking or part picking.
22	Label the axis with x, y and z directions.
23	Modify the Stitch Part Together command to prevent moving the vertices of the added part to the vertices of the home part. This can lead to the loss of geometry information and the creation of large facets.
24	Modify the Show Distance Between Vertices to eliminate the pop-up screen with the computed distance. The distance should show up on the command pop-up screen.
25	Modify the Build Curve command to make the selection of vertices consistent. Sometimes vertices are selected when they are highlighted on the Registry Display and sometimes the user has to click on the "Select" button before the vertex is selected.
26	Address the tendency of GeomFix to crash on simple commands.
27	Modify Delete Narrow Facets command to increase stability. When deleting narrow facets, resulting facets should have larger angles. When deleting triangles with short edges, resulting facets should have longer edges. Provide a preview capability prior to implementation.
28	Improved adaptive mesh refinement schemes

Prioritized Recommendations from LM NE&SS-SS

Relative Priority	DESCRIPTION
1	Provide ability to directly handle quadrilateral facets: Without this capability, the current version of GeomFix must split each quadrilateral into two triangles.
2	Provide capability to split the model along the facet edges closest to a cutting plane – Currently, GeomFix can split the model into one or more pieces along a specified plane(s); however, any facet that is intersected by the cutting plane is itself cut into two or more new facets. For generating smaller ship parts, this process needlessly generates additional facets that in turn impact analysis time.
3	Provide a Limited *"Undo"* capability – This would readily allow some of the recent operations to be undone.
4	Provide support for, and/or associate material properties with the facets or parts.
5	Maintain consistent labels for facets and vertices when deleting. The current version of GeomFix re-labels all higher indices if a facet having a specific index is deleted. Hampering greatly the tracking ability of facets from previous versions.
6	Maintain consistent labels when adding facets and vertices.
7	Provide the capability to select/highlight multiple facets within the Registry Window and filter on various criteria, such as minimum and/or maximum edge length, etc. This function could be associated with other functions specialized to affect only these selected facets, such as: "delete", "replace", etc.
8	Modify the *"Delete Narrow Facets"* function by expanding the dialog window to include both minimum and maximum values for angle and edge length, as well as for other parameters such as facet area. Each parameter could have a check box so that the user can specify parameters of concern to facilitate working on physically large models, or with EM programs with some narrow but large-area facets.
9	Provide a new function *"Delete Selected Narrow Facets"* that selects and displays all facets that meet a definition of "narrow" based on user-inputted threshold values for angle and/or edge length. The user must also be able to inspect it and deselect any facets that they desire to retain.
10	Modify *"Fill Curve"* tool to allow the user to view (as both a text list and highlighted graphically) all of the facets created by the last execution of the *"Fill Curve"* command. This should include a summary of the geometry information relating to just the new facets; thereby, alerting the user of the addition of narrow facets that might otherwise be difficult to detect visually, even if highlighted
11	Provide capability to rotate articulated features such as a gun turret.
12	Provide capability to use the tool as a post-processor so that EM-output data can be visualized and then changes could be directly made to the input model in real time.
13	Provide the capability to suppress the "automatic re-render" function. When using the current version of GeomFix to implement a series of known changes (i.e., discretely deleting a series of unwanted facets by typing in their ID number), it is time consuming to have to wait for the model to be re-rendered after each deletion, especially when working with the comparatively large models of naval ships

The Top 5 Recommended Upgrades to GeomFix from Each Site

Relative Priority	DESCRIPTION
	LMMFC-O
1	Ability to places elements in different "groups", representing different materials identified by different colors.
2	Ability to detect partially overlapping facets
3	Ability to refine meshes using user-specified parameters.
4	Ability to rotate all or part of the geometry about a given line
5	Port GeomFix to Linux Operating System
	LM Aero – Palmdale and Fort Worth
1	Capability to support/specify/track multiple dielectric materials and PEC regions.
2	Capability to migrate element normal information across part boundaries defined by triplets.
3	Capability to maintain the initial model geometry, level of curvature and part boundaries.
4	Provide location and highlighting capability of facets with small angles in Mesh Quality Report.
5	Provide an UNDO command.
	LM NE&SS - SS – Moorestown
1	Provide ability to directly handle quadrilateral facets. :
2	Maintain consistent labels for facets and vertices when deleting facet.
3	Maintain consistent labels for facets and vertices when adding facets.
4	Provide capability to split the model along the facet edges closest to a cutting plane
5	Provide support for, or associate material properties with the facets or parts.

LM's Recommendations Consolidated and Categorized by Matis

	Tasks	Recommended by (LM Company & Recom. # — pp15-17)
1	Provide Capability to Assign/Change/Repair Multiple Materials	LMMFC-O 1 LMAero 1, 2, 11 LM NE&SS-SS 4, 5, 6, 7
2	Facilitate Arbitrary Rotation to Accommodate Changes in Geometry Due to Moveable Parts (Gun Barrels, Turrets,..)	LMMFC-O 4 LM NE&SS-SS 11
3	Utilize GeomFix as CEM Post-processing Tool	LM NE&SS-SS 12
4	Introduce Mechanism for User Defined Macros	LMMFC-O 10
5	Repair Models Represented by Quadrilateral Facets	LM NE&SS-SS 1
6	Port GeomFix to Linux to run on PCs	LMMFC-O 5
7	Expand UNDO Capabilities	LMMFC-O 5, 7 LM NE&SS-SS 3
8	Complete Investigation for Integration with ACAD	LMMFC-O 12
9	Expand Mesh Quality Improvement Functions --additional Mesh Refinement/Decimation Functionality --additional Control/Removal of Narrow Facets --additional Alerts & Warnings of Geometry Changes	 LMMFC-O 3, 9 LMAero 6, 9, 14, 28 LM NE&SS-SS 8, 9, 10 LMMFC-O 2 LMAero 3, 17
10	Additional Enhancements of 3D Rendering	LMAero 12, 14, 15, 16, 22 LM NE&SS-SS 13
11	Work in Progress: Various Modifications and Enhancements Completed by Matis (to Be Included in the Next Release)	LMMFC-O 7, 8, 11 LMAero 4, 6, 8, 13, 18, 19, 20, 21, 23, 24, 25, 26, 27 LM NE&SS-SS 2

5 Overall Conclusions

This section is a summary of conclusions from the Final Report by Lockheed Martin (see pages 6-7 of the attached Final Report by Lockheed Martin).

Overall, GeomFix has great potential for use on LO platform design and analysis for CEM mesh models at Lockheed Martin. Currently, GeomFix can act on any triangular faceted file provided to it in an acceptable format no matter what the source of the triangles. This flexibility and neutrality is decidedly convenient.

The graphical user interface (GUI) and robust 3-D visualization associated with GeomFix are straightforward and intuitive to use. The tool allows a user to correct many of the difficulties discussed above that are associated with meshed models quickly and automatically. Other problems with a model can often be identified and corrected interactively using the existing GeomFix GUI and 3-D visualization.

The use and training is also very straightforward and intuitive. GeomFix is usable by a typical CEM engineer with a minimal amount of training. Two independent users, experienced in CAD, repaired a faceted file using GeomFix and obtained similar RCS results (within 0.6 dB average) using the same CEM code. The differences were due to the two users selecting and generating a different number of facets.

Lockheed Martin was encouraged by and supports the approaches used by GeomFix to automate the repair process of mesh geometries for analysis by MM3D, an exact CEM solver. The reduced triangle edge length and the deletion of 'T-Junctions' functions, already incorporated into GeomFix, are usually repaired by hand or blind automation without graphical review at LMMFC-O. This can generate errors that add hours to mesh preparation.

GeomFix also has great potential for use on Naval platforms at LM NE&SS-SS. The GUI and 3-D visualization allowed users to quickly correct many of the problems associated with meshed models. Over the past several years, the Signatures Technology Group at LM NE&SS-SS has worked part-time to develop it's own software tools that, like GeomFix, facilitate the trouble-shooting, correcting and optimizing of faceted model files derived from CAD structural models. As such, they are in a position to appreciate the significant leap forward that GeomFix offers compared to existing tools.

Future CEM tools will require even more stringent mesh handling processes. The repair and analysis tools needed to support the increased requirements are more likely to be created by small companies such as Matis than by the large CAD companies.

To enhance applicability of GeomFix to existing and developing CEM design and analysis tools, it is recommended that the next phase in development and enhancement of GeomFix include implementation of users' recommendations (see Appendix A in Final Report by Lockheed Martin).

6 Appendix - Final Report by Lockheed Martin (separate volume)

The Final Report by Lockheed Martin is included in this submission as a separate volume.